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Radon in U.S. workplaces, a review

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Abstract

Exposure to naturally occurring radon is unavoidable and is second only to smoking as a direct cause of lung cancer in the United States (U.S.). The literature for existing information on U.S. occupations that are prone to increased radon exposures was reviewed. Current recommendations and applicable protective standards against occupational radon exposure that are applicable to U.S. workers are discussed.

Exposure varied widely among several working populations, most of whom were employed in industries that were unrelated to the uranium fuel cycle. Radon protection standards differed among agencies and have not changed since the height of domestic uranium production in the 1970s. In contrast, European countries are adopting recommendations by the International Commission on Radiation Protection to set a reference level near a derived annual exposure of about one working level month, which is 25% of the level currently established for U.S. miners.

INTRODUCTION

Radon gas (Rn) is a colorless, odorless, inert, radioactive noble gas within the uranium decay series. Its major isotopic form is Rn222, which is the immediate progeny of Ra226 decay. Radium is a natural primordial radioactive element that is found ubiquitously in the earth's crust, water, and in many building materials; therefore, exposure to radon is unavoidable. The term "radon" typically refers to the combination of Rn and its short-lived decay products (RnDP); however, nearly all of the inhalation dose is from densely ionizing alpha radiation from respired RnDP that are deposited throughout the respiratory tract, but most importantly on the bronchial epithelium[(1)]. Radon exposure accounts for about a third of the annual per capita effective radiation dose in the United States (U.S.)[(2)].

Studies of underground uranium miners and residences have unequivocally established radon as a human lung carcinogen[(3–5)]. According to the U.S. Environmental Protection Agency (EPA), radon is the second leading cause of lung cancer in the U.S., and is the leading cause among never smokers[(6)]. In efforts to reduce the burden of lung cancer, the EPA has established a derived reference level (DRL) for radon in dwellings of 148 $Bq{\cdot}m^{-3}$ Rn222, above which efforts to reduce exposures are strongly recommended. The estimated excess lifetime lung cancer risk for continuous exposure at the EPA DRL is 2.3% for the

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U.S. population: 4.1% for ever-smokers, and 0.73% for never smokers. The excess absolute risk is higher for smokers than non-smokers because the form of interaction between radon and smoking is more than additive[7]. The EPA DRL is slightly less than comparable values in other developed countries, where most lie between 200 and 400 Bq·m^{-3} Rn222[8].

Occupational sources of radon exposure are well known in the uranium mining and milling industry. As such, a system of protection against these exposures exists to ensure uranium workers are equipped and trained to mitigate their exposure-related risks. In the U.S., these protections were primarily developed at the height of the Cold War, when the demand for uranium was greatest. The decline in nuclear weapons production and commercial nuclear power over the past three decades has led to a reduction in the U.S. uranium industry. As the workforce shrinks, less emphasis may be placed on updating worker protections; therefore, periodic evaluation of longstanding requirements is needed.

Perhaps more importantly, occupational radon exposure is not limited to underground uranium miners; therefore, other underground work that is not typically associated with radiological hazards may be conducted with little regard for radon exposures. Less is known about radon in these workplaces, and workers tend to be uninformed of their occupational exposure and consequent health risks. This paper reviews the current status of occupational radon exposure in the U.S. Affected working populations are identified, the potential for exposure by occupational sectors is examined, and standing recommendations and regulations for workplace protection are discussed.

METHODS

The English language literature was systematically searched for information related to occupational radon exposure in the U.S. Relevant peer-reviewed articles, proceedings, and technical reports were identified using a key word search of public domain citation databases. Abstracts were reviewed to determine the applicability of articles under consideration. Citations within informative articles were also examined. Demographic information for affected working populations was obtained from databases maintained by Bureau of Labor Statistics (BLS). Inspection reports were obtained from the U.S. Nuclear Regulatory Commission (USNRC) and examined for information on occupational doses from radon exposures in licensed facilities. Datasets maintained by the Mine Safety and Health Administration (MSHA) were searched for information on U.S. mine characteristics, including radon monitoring data, to estimate mean, median and standard deviations of exposure measurements. All data analyses were conducted using SAS software[9].

RESULTS

Recommendations and Regulations

International level—In its most recent recommendations on radon exposure, the International Commission on Radiological Protection (ICRP) encouraged national authorities to set a radon reference level (RL) based on an annual effective dose within the range of 1 to 20 mSv for members of the public and workers alike[10]. The ICRP suggested a benchmark of 10 mSv effective dose equivalent per year as a practical starting point for considerations by nations developing radon management strategies and also recognized an effective dose conversion factor (DCF) for RnDP exposures of approximately 10 mSv per Working Level Month (WLM), where 1 WLM =3.54 mJ·h·m^{-3}. Thus, the DRL is 1 WLM·y^{-1}, or average annual Rn222 concentration of about 200 and 800 Bq·m^{-3} at home and in the workplace, respectively (Table 1). The ICRP also recognized that planned occupational exposures above the RL may be unavoidable. In those cases, the exposure should be treated as occupational and managed using a set of radiation protection requirements for radiation workers. However, a worker's annual effective dose from radon should be kept below 20 mSv after accounting for the exposure situation (e.g., equilibrium, occupancy, breathing rate, respiratory protection, etc.).

The European Union (EU) has adopted the ICRP's recommendations into its protection standards. Member states are required to develop national action plans for addressing the long term health risks of radon exposure in workplaces by February 2018[(11)]. The EU recommends 300 Bq·m^{-3} for Rn222 concentrations as a suitable radon DRL, although provisions for selecting a different level have been offered. Ireland was first to respond by publishing the National Radon Control Strategy in 2014[(12)]. The plan established a workplace DRL of 400 Bq·m^{-3} Rn222, measured over three consecutive months. Exceeding the DRL triggers immediate federal notification and an evaluation by the employer to determine if remediation is justified. Remediation is mandatory if the average Rn222 level exceeds 800 Bq·m^{-3}.

National Level (United States)—The National Council on Radiation Protection and Measurements (NCRP) first published recommendations on radon exposure in 1984. The NCRP advised against exceeding an excess risk of death from lung cancer of 2% or greater over the lifetime of any individual exposed to enhanced levels of radon. Using the underground miner epidemiologic data available at the time, the NCRP related this risk to RnDP exposures of 2 WLM·y^{-1} (Table 1)[(13)]. These risk projections and recommendations were revisited by the NCRP in its 1993 report on public and occupational exposure limits, but the DRL of 2 WLM·y^{-1} was retained despite an increase in the projected lifetime risk at this level[(14)]. This NCRP DRL applied to public exposures indoors; occupational radon exposure was not explicitly addressed. However, the NCRP recommended that the effective dose from ionizing radiation exposure in the workplace be kept below 50 mSv in a year and recognized a radon exposure dose conversion convention of 10 mSv per WLM. Thus, the inferred recommended limit for workers is 5 WLM·y^{-1}, in the absence of other sources of occupational radiation exposures. In contrast to external radiation, the detriment from radon exposure is due only to lung cancer; thus, the excess absolute risk of lung cancer mortality if exposed at this limit over a working lifetime is quite substantial (on the order of 10%).

The American Conference of Governmental Industrial Hygienists (ACGIH) derived a threshold limit value (TLV) for RnDP exposure of 4 WLM·y^{-1} based on the 1993 ICRP recommendations (Table 1)[(15)]. However, the ACGIH also refers to an upper value for an individual worker's annual effective dose from radon of 10 mSv, which is related to the workplace action level for Rn222 of 1.5 kBq·m^{-3} that was also specified by the ICRP in 1993, based on a gas/progeny equilibrium fraction equal to 0.4 and a DCF of 5 mSv per WLM[(15)].

In 1987, the National Institute for Occupational Safety and Health (NIOSH) recommended that annual RnDP exposures to workers in underground mines should not exceed 1 WLM (Table 1)[16]. The NIOSH recommended exposure limit (REL) was intended to address the protection of underground uranium miners and did not consider radon exposure in other occupations. Although a risk assessment was conducted, the NIOSH REL was ultimately based on the feasibility of lowering exposure levels in underground mines given control technologies available at the time.

In the U.S., occupational radiation protection standards are promulgated by multiple federal agencies, such as the USNRC, MSHA, the U.S. Department of Energy (DOE), and the Occupational Safety and Health Administration (OSHA). These standards have not been harmonized with respect to the protection against occupational radon exposure. MSHA established an annual exposure limit on RnDP of 4 WLM (30 CFR §57.5038), which was first adopted for U.S. miners in 1971 (Table 1)[17]. MSHA also established a maximum permissible concentration for RnDP concentrations in occupied areas of one working level (WL) (30 CFR 57.5039), where 1 WL= 20.8 $\mu J \cdot m^{-3}$. Similarly, the USNRC established an annual limit on intake (ALI) for RnDP of 4 WLM and a corresponding derived airborne concentration (DAC) for RnDP of 0.33 WL (10 CFR 20, Appendix B, Table 1)[18]. In contrast, the DOE instituted an ALI of 10 WLM (10 CFR 835, Appendix A, footnote 5)[19] based on a now obsolete estimate of lung cancer detriment from radon (i.e., 2.8×10^{-4} per WLM)[15]. The OSHA permissible exposure limit (PEL) for Rn222 exposures is 3.7 $kBq \cdot m^{-3}$ averaged over 40 hours in any workweek of 7 consecutive days, which is equivalent to an RnDP concentration of 1 WL in complete progeny equilibrium (29 CFR 1910.1096(c)(1))[20]. The OSHA PEL is taken from the airborne radioactive materials exposure limits in Table I and Table II of Appendix B to 10 CFR Part 20 that was published in 1969 and stems from the earlier miner limit of 12 $WLM \cdot y^{-1}$ set by the Federal Radiation Council[21]. This has been a source of confusion when interpreting the OSHA standard, given a revision to the standard shortly thereafter reducing the radon exposure limit.

Affected Workplaces

Underground Mining—The BLS reports there were more than 63,000 workers employed in U.S. underground mines in 2014. These workers were employed in mining bituminous coal (68%), metals (15%), nonmetals (10%) and stone (7%). Underground atmospheres have increased potential for radon exposure, especially in mining of uranium and associated substances such as copper, phosphorous, calcium, arsenic, barium, vanadium and lead. For example, 28% and 1% of underground uranium miners working in 1984 (~1,500 miners) received an annual exposure in excess of 1.0 WLM and 4.0 WLM, respectively[16]. Contemporary measurement data are available from MSHA, comprising measurements of multiple agents distributed among several mine types; however, radon RnDP measurements were available for only 4% of all monitored mines. Monitoring RnDP is conducted by grab sampling and values are determined in potential alpha energy concentration (PAEC) in units of WL. The data were restricted to 3,538 measurements from sampling in 328 underground mines between the years 2000 and 2015 (Table 2). Arithmetic mean and median PAEC values were calculated for all underground mines and by mine type, with median values providing a more stable measure of central tendency due to heavily right-skewed sample distributions. The overall median PAEC was 0.01 WL and values among mine types ranged from null to 0.28 WL, with the highest median value obtained for uranium and vanadium mines. The MSHA database also contained a few (n=8) personal PAEC measurements for underground miners during this period. Of these, the maximum PAEC was 24.2 WL; however, no measurements exceeded the maximum permissible concentration after accounting for respiratory protection. In summary, the MSHA data suggest that annual uranium miner exposures in excess of 4 WLM are unlikely as long as the use of forced ventilation and respiratory protection continue.

Data on radon in U. S. coal mines were not found in the MSHA database; however, there were a few related studies. Air sampling in seven Colorado lignite coal mines revealed average radon concentrations ranging from 0.3 to 5 kBq·m^{-3} [22]. Lucas and Gabrysh (1966) surveyed 16 coal mines in Pennsylvania and found radon concentrations ranging from about 10 Bq·m^{-3} to 5.4 kBq·m^{-3}, with a median concentration of about 0.1 kBq·m^{-3} [23]. They noted that uranium minerals such as autunite, uranophane, and carnotite were not common to the sampled mine locations. A followup study added nine mines located in West Virginia, Kentucky and Tennessee and found radon concentrations that were comparable to that in Pennsylvanian mines but exceeding 40 kBq·m^{-3} in one mine[24]. Neither study addressed mine occupancy, adequacy of worker protection, or estimated miner exposure or dose.

Information on radon in other U.S. non-uranium mines is sparse. Harris (1954) examined several non-uranium underground mines in New York and reported airborne Rn222 concentrations ranging from 0.26 to 5.2 kBq·m^{-3} in iron mines, 0.26 to 2.3 kBq·m^{-3} in talc mines, and 0.04 to 0.22 kBq·m^{-3} in zinc mines[25]. NIOSH examined the MSHA measurement data from 254 non-uranium mines operating between 1984 and 1985[16]. Of these mines, RnDP measurements in excess of 0.1 WL were found in 38 mines and seven had concentrations of 1.0 WL or greater.

Uranium Production—The current U.S. uranium industry continues on a relatively small scale compared to the Cold War Era, with an average annual uranium production of less than 2,000 metric tons over the last decade[26]. The industry employs about 1,000 workers and about two-thirds of the workforce is attributed to mining, milling and processing uranium. For milling and processing, eight in-situ-leach (ISL) plants and one operating uranium mill accounted for all U.S. production in 2014. The mill employs about 150 workers and produces about 400 metric tons per year, which is far below capacity (1,800 metric tons per day). There were 19 PAEC measurements available during mill operations between 2000 and 2015, resulting in a median PAEC below 0.01 WL. No measurement exceeded 0.02 WL. There was little information on radon exposures among U.S. ISL workers. The review of USNRC inspection reports indicated that 40 to 70 workers were monitored annually for radiation exposures in each operating plant. The inspection reports also suggested that the average maximum annual exposures for ISL plants in 2014 was about 0.1 WLM (range 0.02–0.15 WLM); however, reports were only available for six plants. A study of multiple ISL plants reported average radon levels ranging from 0.4 to 18 kBq·m^{-3} in production areas. This same study also reported a peak concentration exceeding 13 MBq·m^{-3} directly above a process fluid tank vent in one plant[27]. However, the high radon concentrations from dissolution are likely to be in extreme progeny disequilibrium in modern ventilated workspaces. Unfortunately, there was no accompanying information on the equilibrium fraction, attached fraction or other dosimetric parameters. Information on individual dose from occupational exposures in ISL plants was not available.

Phosphate Production—Uranium, thorium, and radium are common radioactive impurities of phosphate rock, with mass-based uranium concentrations in U.S. deposits ranging from 10 to 400 ppm[(28)]. Phosphate fertilizer production requires the mining, beneficiation, and milling of phosphate rock for the manufacture of phosphoric acid. These processes liberate radon, resulting in above background concentrations in some indoor and outdoor workplaces. In 2014, 11 mines were operated in 4 states to produce about 27 million tons of marketable phosphate product. About 80% of the domestic output is attributed to Florida and North Carolina operations while the remainder is produced in Idaho and Utah[(29)]. BLS data suggest that the U.S. phosphate workforce currently comprises about 1,500 employees. Radon concentrations in most U.S. phosphate work areas appear low, with reported average concentrations typically below 50 $Bq \cdot m^{-3}$ in most occupied areas[(30)]. The highest concentrations were observed in rock tunnels, where average values were on the order of 1.9 $kBq \cdot m^{-3}$ and maximum values approached 3.0 $kBq \cdot m^{-3}$. However, the rock tunnels were mostly unoccupied, with infrequent entry made by some workers to clean up spills and repair conveyor systems. In addition, these areas were ventilated prior to entry, resulting in RnDP concentrations that were consistently low (<0.95 mWL)[(30)].

Waterworks—In 2014, there were 111,600 U.S. workers classified as water and wastewater treatment plant operators by the BLS. A nationwide survey of radon in groundwater supplies reported an average U.S. concentration of about 13 $kBq \cdot m^{-3}$, with state averages ranging from about 3 to 50 $kBq \cdot m^{-3}$ and localized maximum values exceeding 500 $kBq \cdot m^{-3}$ [(31)]. Processing groundwater can result in dissolution of radon and increased potential for occupational exposures.

Studies of occupational radon exposures in U.S. waterworks are sparse. Fisher et al. (1996) examined in-air radon concentrations at 31 water treatment facilities in Iowa. They found annual average radon concentrations ranging from 0.02 to 4.9 $kBq \cdot m^{-3}$. In a small comparison of three workers monitored at work and at home, none had higher occupational exposures compared to home levels; however, Fisher et al. (1996) concluded that employees working longer hours in some plant areas may accumulate exposures exceeding 4 WLM annually[(32)].

In-air radon concentrations in excess of 3.0 $kBq \cdot m^{-3}$ have been reported in workspaces at fish hatcheries where groundwater is aerated indoors[(33–35)]. A survey at one of the hatcheries indicated low worker exposures (e.g., <0.2 $WLM \cdot y^{-1}$) despite high radon concentrations, due primarily to low occupancy times in affected buildings[(33)]. In another hatchery, where occupancy times appeared much greater, the estimated average annual worker exposure (prior to mitigation) was 1.2 WLM[(34)].

Tourist Caves and Abandoned Mines—There are thousands of national, state, and privately own tourist caves, karsts and abandoned mines across the U.S. The workforce in these locations consists primarily of services personnel (tour guides, concessions, and maintenance workers) and scientists. A collection of several studies suggest that radon concentrations vary widely among caves, with average concentrations ranging to nearly 7.0 kBq·m^{-3} at some locations[36–47]. The potential for significant occupational radon exposures in U.S. show-caves first received attention in the 1970's from studies by the National Park Service (NPS)[37–41]. The early NPS data suggested that, on average, annual worker exposures exceeded 1 WLM for several workers and may exceed 4 WLM for a few workers in many national caves. In response, the NPS began a radiation protection program to advise workers of the hazard, prohibit smoking in caves, and reduce annual radon exposures to levels below 4 WLM. Among NPS workers monitored, the highest exposures were obtained in Mammoth Cave located in Kentucky, where adjustments to work assignments and tours were necessary. Recent reports suggest that the NPS later reduced the DRL to 3 WLM·y^{-1} at Mammoth Cave and continues to monitor radon concentrations for compliance purposes[48].

There is little information on radon exposures among U.S. cave workers employed outside of the NPS. One study conducted monitoring in 71 private and state show-caves and found overall and peak cave average PAEC values of 0.53 and 6.5 WL, respectively. About 30% of the monitored caves had a gift shop or some other routinely occupied building directly attached to the cave, where peak values exceeding 5.0 WL were found. The relatively high PAEC values were offset by low annual occupancy; the average number of hours worked underground per calendar year was 270 hours, although a full work year (2000 hours) was achieved by some workers. Worker turnover in the industry appears high; nearly half of tourist-cave employees have careers spanning four months or less.[49].

Although data on radon levels in commonly visited sites within the NPS are available, there is less information on remote locations that may be frequented by researchers (e.g., geologists, archeologists, and biologists) and other workers. In the U.S., there are approximately 300,000 abandoned mine openings, of which only a small percentage have been made inaccessible by mine closure activities[50]. As in caves, radon measurements in abandoned mines or mines operated without forced ventilation have varied greatly; however, some mine concentrations have exceeded 1.0 MBq·m^{-3} [51, 52]. At this level, an effective dose on the order to 10 mSv may occur from exposures lasting less than two hours.

Alternative medicine—Speleotherapy (i.e., the use of subterranean environments in treatment of disease) and balneotherapy (i.e., the treatment of disease by bathing in mineral springs) are long-standing practices in many Asian and European countries. A key component of these therapies is intentional radon exposure by inhalation or absorption of radon dissolved in water, which is believed to alleviate symptoms from a wide array of diseases, injuries, and medical ailments. There is sparse evidence supporting the efficacy of radon-therapies, primarily for rheumatic disease and asthma, in which some studies suggested radon has analgesic, anti-inflammatory, and immune stimulating effects[53–55]. Still, speleotherapy and balneotherapy are generally labeled as alternative therapies in the U.S. and are typically not recommended by physicians[56, 57]. Nevertheless, there are approximately 100 major geothermal spas and about a half dozen radon 'health mines' and therapy centers operating in the U.S[56, 57]. Persons working in these facilities are potentially exposed to enhanced levels of radon as a condition of their employment.

Information on radon exposures in U.S. spas and health mines is sparse. Given appreciable size and popularity, the 47 hot springs of the Hot Springs National Park in Arkansas have been studied most, with radiation studies beginning in the early 1900s. Results from multiple studies reported radon in water ranging from 0.6 to over 1000 kBq·m^{-3} [58–60]. A 2004 survey reported measurements of radon in air that ranged from 1.7 to 3.3 kBq·m^{-3} in occupied indoor spaces and reaching a maximum of about 8.3 kBq·m^{-3} in an infrequently occupied crawlspace[61]. The wide range in observed concentrations was attributed to varied source terms and ventilation patterns. Levels in these areas were subsequently reduced below 100 Bq·m^{-3} following remediation efforts.

Other Workplaces—Workers may also be exposed to radon in many less-known occupations and workplaces. Work in locations below grade, such as tunnels, subways, trenches, basement offices and homes (e.g., radon abatement work), presents an increased potential for radon exposure. Moreover, aboveground locations that are poorly ventilated or constructed with radium bearing materials may also pose a substantive radon hazard. For example, a recent survey in Missouri found radon concentrations exceeding the EPA DRL in approximately 10% of aboveground workplaces[62]. These findings were in very good agreement with earlier workplace assessments of federal facilities[63, 64]. As another example, area radon measurements in British telecommunications tunnels revealed an overall average concentration of 1.4 kBq·m^{-3} and regional averages ranging from 0.8 to 2.5 kBq·m^{-3} [65]. Personal radon dosimetry was conducted on workers assigned to these tunnels over a 30 day monitoring period. Using the measurement data, the estimated average annual effective dose was below 5 mSv·y^{-1} for most workers; however, estimates for some workers exceeded twice that amount in certain situations. In another study, measurements of indoor radon concentrations in 22 underground rooms of eight Slovenian wineries ranged from 0.03 to 1.0 kBq m^{-3}. The estimated maximum effective dose to winery workers was about 6 mSv·y^{-1} [66].

DISCUSSION

There are over a thousand uranium miners, and over 100,000 U.S. workers employed in industries unrelated to the uranium fuel cycle (e.g., other underground mining, waterworks, phosphate production, and tourist caves), who are potentially exposed to elevated radon levels in the workplace. Exposure characteristics vary widely by employment sector. RnDP concentrations appear greatest in abandoned mine and show-caves; however, the collective dose attributable to exposures in these work areas is tempered by the relatively small size of the workforce and shorter stay times of individual employees. In contrast, U.S. waterworks employees comprise the largest affected workforce, but workers, on average, are likely exposed to lesser RnDP concentrations compared to those found underground.

Radon exposure controls and other risk management practices appear best for miners, particularly those working in uranium and vanadium mines. In contrast to uranium mining and production, there was little information on practices to mitigate radon risk in other U.S. industries. Given the ubiquity of radon, adventitious exposures to elevated radon levels are common but rarely considered occupational; therefore exposures tend to be poorly characterized and worker protections are seldom used. Findings from this review suggest that in the absence of adequate controls, individual lung doses from occupational exposures outside of the uranium fuel cycle (e.g., tourist cave workers, waterworks employees) can exceed those found in most uranium workers. Overall, more work is needed to characterize U.S. workplaces for radon exposure, reduce these exposures, and inform the workforce on associated risks.

Nearly all U.S. standards on occupational radon exposure have remained unchanged since the height of domestic uranium production; whereas radon policies have continued to evolve in many other developed nations. Moreover, U.S. standards are compartmentalized and differ between regulating agencies, which may be a source of uncertainty for U.S. workers. In contrast, most European countries have universally adopted the recent ICRP recommendations and are now drafting national action plans for occupational and public radon exposures. At the time of this review, it is unclear whether a similar approach is being considered by U.S. regulators. We note that the benchmark ICRP RL value (10 $mSv \cdot y^{-1}$) aligns with the NIOSH REL (1 $WLM \cdot y^{-1}$) for underground miners and the ACGIH guidance for an upper dose. Thus, a potential point for adopting a single DRL value for occupational radon exposure is supported by existing U.S. recommendations.

A DRL of 1 $WLM \cdot y^{-1}$ may be suitable for a 10 mSv equivalence in most exposures settings, but not for show-caves or abandoned mines. Unlike operating mines, forced ventilation is generally prohibited in show-caves to protect the natural microenvironment. The lack of forced ventilation results in higher radon gas concentrations and maximizes progeny ingrowth; therefore, worker exposures can be much greater than that found in active mines[(67)]. Poor mixing and the general lack of suspended particles, especially in arid conditions lacking airborne condensate nuclei, increases the fraction of the potential alpha energy concentration that is unattached to ambient aerosols, which results in greater deep lung dose per unit exposure. A series of measurements in the late 1990s revealed an unattached fraction in the Carlsbad Caverns ranging from about 30% to 60%[(46)]. Similar findings have been reported in show-caves elsewhere[(68, 69)]. In comparison, the unattached fraction is typically about 10% in homes and 1% in active mines[(1)]. Given that most published dosimetric-based DCFs are derived for mining or home environments, their use in assessing exposures to cave workers substantively underestimate dose.

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Table 1

Applicable protection standards and guidance for occupational exposure to radon progeny

Standard Type	Agency	Reference	Covered Population	Annual Level (WLM)
Guidance	ICRP	Publication No. 126	All	1
	NCRP	Report No. 77	Public	2
	ACGIH	2011 TLVs® and BEIs®	Workers	4
	NIOSH	Publication No. 88-101	Underground miners	1
Regulation	DOE	10 CFR 835, Appendix A	DOE Workers	10
	MSHA	30 CFR Part 57	Underground miners	4
	USNRC	10 CFR 20, Appendix B, Table 1	Licensee workers	4
	OSHA	29 CFR 1910.1096, 29 CFR 1926.53	Workers not regulated by DOE, MSHA, or NRC	12

Abbreviations: ACGIH, American Conference of Governmental Industrial Hygienists; BEI, biological exposure index; CFR, Code of Federal Regulations; DOE, U.S. Department of Energy; ICRP, International Committee on Radiological Protection; MSHA, Mine Safety and Health Administration; NCRP, National council for Radiation Protection and Measurements; NIOSH, National Institute for Occupational Safety and Health; TLV, threshold limit value; USNRC, U.S. Nuclear Regulatory Agency, WLM, working level month (1 WLM = 3.54 $mJ \cdot h \cdot m^{-3}$).

Table 2

Results from radon progeny area monitoring in U.S. underground mines from 2000 to 2015[1].

Mine type	Mines (n)	Mine Operations (person-years)	Samples (n)	PAEC (WL)		
				Mean	Median	Interquartile range
All	328	25183	3538	0.79	0.01	0.05
Metals	138	10771	1317	0.20	0.03	0.19
Uranium/vanadium	20	112	461	0.50	0.28	0.46
Gold	74	3017	378	0.04	0.00	0.03
Lead-zinc	17	3982	232	0.03	0.02	0.03
Silver	10	1313	118	0.04	0.01	0.02
Other metals	17	2347	128	0.08	0.03	0.11
Nonmetals	48	8593	557	0.06	0.00	0.02
Salt	14	1907	312	0.08	0.00	0.02
Trona	4	4705	66	0.01	0.00	0.01
Gemstone	4	12	55	0.08	0.04	0.08
Other nonmetals	26	1969	124	0.03	0.00	0.02
Stone and sand	142	5819	1664	1.49	0.01	0.02

[1]Compiled from the MSHA database accessed mid-October 2015.

MSHA, Mine Safety and Health Administration; PAEC, potential alpha energy concentration; WL, working level (1 WL = 20.8 $\mu J \cdot m^{-3}$).